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Effect of process parameters on dimensional accuracy of fiber-reinforced thin-walled micro moulded part

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Abstract

Micro injection moulding is one of the most established processes for precise manufacturing of 3D complex micro components; however, the achieved precision varies greatly with respect to the process parameters. Production of micro connectors is one of the applications where high precision is demanded due to the complexity of features and strict tolerances. In addition, the use of fiber-reinforced polymers affects the desired accuracy, which is attributed mainly to the orientation of fibers in the final part. In this work, the effect of the processing parameters on shrinkage, fiber orientation and dimensional accuracy of glass fibre-reinforced micro injection moulded parts was studied with reference to a simplified geometry. The results indicated that micro injection moulding parameters affect the dimensional accuracy of the moulded parts, by changing the skin-core morphology within their thickness. Moreover, the fiber orientation analysis of the parts showed that the reduced thickness of mould cavity lead to the disappearance of the core layer, in favour of the predominant skin layers.

dimensional accuracy, shrinkage, fibre orientation, micro-CT, micro injection moulding

1. Introduction

Precision manufacturing of thin-walled micro parts produced by injection moulding recently attracted large attention for microelectronics applications owing to their increasing market demands [1]. However, the commercial breakthrough of new and smaller micro connectors strongly depends on the necessity to develop low cost mass fabrication technologies such as micro injection moulding (µIM).

Shrinkage and warpage are common defects resulting from the µIM process that can compromise the quality and the functionality of the final parts [2]. In this sense, reducing and controlling shrinkage is very important to achieve high dimensional accuracy of products, especially when manufacturing parts with close tolerances [3]. Furthermore, the use of reinforced polymers leads to some processing issues, related to the anisotropic distribution of the fibres within the parts, which eventually affects the shrinkage of the parts [4].

Several researchers have studied how the fibre orientation tensor is affected by the injection moulding processing parameters [5]; however, the relation between fibre distribution and shrinkage of the parts has not been thoroughly investigated yet.

Experimental studies demonstrated that shrinkage is affected by scale effects, especially due to the different morphology of the thin-walled parts, which is caused by the high shear rates that characterize the process [6]. In general, fibre orientation within injection moulded parts is explained considering the 'fountain flow' model [7]: the shear effect is more prominent in the skin layer and so is the orientation in the melt flow direction; whereas, in the core region the melt flow is subjected to minimum shear, thus the orientation in the flow direction is considerably lower. However, the very small thickness of the part can modify this behaviour, by changing the thickness ratio between the skin and core layers [8].

In this work, the effect of process parameters on the dimensional accuracy of thin-walled injection moulded micro parts was experimentally investigated. The design of experiments (DoE) approach was followed to well understand the correlation.

2. Materials and methods

2.1. Micro injection moulding setup

A commercial polybutylene terephthalate PBT (BASF, Ultradur B4300 G2) reinforced with short-glass fibers (10% in weight) was used to mould square plaques with a side length of 10 mm and a thickness of 0.35 mm (see figure 1).

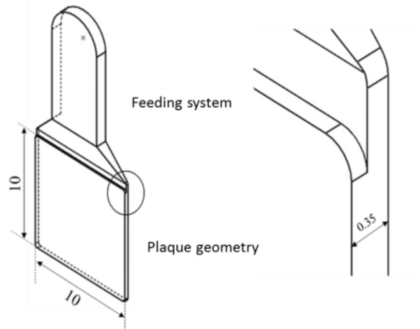

Figure 1. Thin-walled plaque geometry (all dimensions are in mm).

A state-of-the-art injection moulding machine (Wittmann Battenfeld, MicroPower 15) was used for the experiments. Melt temperature (T_b), injection speed (V_{inj}), cooling time (t_c) and packing pressure (P_h) are the most important factors that can affect the final part quality; however, cooling time was excluded from the DoE based on initial investigation (see table 1).

Table 1. Process parameters settings for the shrinkage DoE plan.

Factor	Low level	High level
T_b/°C	270	290
V_{inj}/mm/s	200	600
P_h/bar	200	600

2.2. Characterization of the moulded parts

The dimensional measurements of the parts were performed by means of a multi-sensor coordinate measuring machine (Werth, Video-Check-IP 400). The shrinkage of the moulded parts was then calculated as a percentage reduction from mould dimensions.

X-ray computed tomography (CT) was used for fiber orientation analysis [9, 10]. A metrological µ-CT system (Nikon Metrology, X-Tek MCT 225) was used for acquiring projections (main scanning parameters are shown in table 2). The obtained µ-CT dataset was then processed and fiber orientation measurements were obtained using VGStudio MAX 3.0.

Table 2. CT scanning parameters.

Voltage	Current	Projections	Voxel size
95 kV	74 µA	2500	8.3 µm

3. Results and discussion

3.1. Effects of process parameters on shrinkage

The results of the analysis of variance (ANOVA) indicated that the melt temperature and the packing pressure are the parameters affecting the dimensional accuracy the most, both in terms of parallel shrinkage (figure 2) and transverse shrinkage. Moreover, the injection speed was observed to affect the shrinkage, but only in the perpendicular direction.

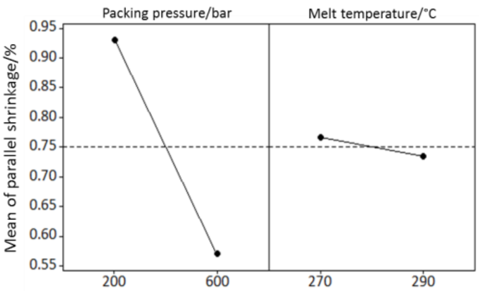

Figure 2. Main effect plots of packing pressure and melt temperature for the shrinkage in the flow direction.

By varying, the packing pressure from 200 to 600 bar, the shrinkage is reduced both in the flow direction (-35%) and in the transverse direction (-31%). The shrinkage of the micro parts was also reduced by increasing the melt temperature. This is explained by considering the PVT behaviour of the polymers. The higher the pressure applied to the polymer, the lower its specific volume and its shrinkage.

3.2. Fibre orientation analysis

The analysis of fibre orientation performed using µ-CT data enabled the calculation of the orientation tensor, which was evaluated considering its average and maximum values. As expected, the fibre orientation is affected by different selection of process parameters. In particular, higher melt temperature yielded a reduction of fibre orientation by -7% due to thinner shear layers within the micro parts. Moreover, high values of the injection speed led to a reduction of fibre orientation (-11%) which is attributed to the modified skin-shear-core morphology along the thickness (figure 3).

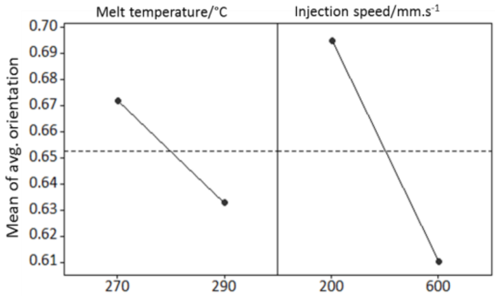

Figure 3. Main effect plots of melt temperature and injection speed for fiber orientation in flow direction.

Figure 4 indicates that the thickness ratio between the shear and core layers is affected by the process, and in particular by the injection speed. Indeed, the extremely thin-walled cavity resulted in an almost flat trend of the orientation tensor for parts moulded at lower injection speed, which indicated the absence of the core layer. The consequence of that was a higher shrinkage along the cross-flow direction that eventually led to a differential shrinkage and to the warpage of the final part.

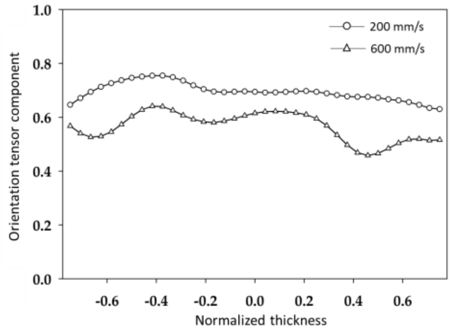

Figure 4. Average fiber orientation tensor in the flow direction.

4. Conclusions

The analysis of variance applied on the experimental data showed that melt temperature and packing pressure are the most significant parameters affecting the shrinkage. The injection speed yielded a positive effect on the dimensional accuracy but only in the transverse direction.

The analysis of fibre orientation indicated that a high selection of process parameters yielded a reduction of fibre orientation in the flow direction. Furthermore, it was observed that the thickness ratio between shear and core layers is affected by the injection speed which resulted in differential shrinkage and warpage of the final part.

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